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Energy Efficiency and Renewable Energy Division

Renewable energy especially solar, wind and biomass was recognized as the future energy source for India during the late 1960s and 1970s. CPRI installed water pumping windmills as early as 1976. The CPRI began the work in energy efficiency in 1979 recognizing its importance to the power sector. The work began with product development for energy efficiency and renewable energy and branched out into consultancy services for energy audits and power plant engineering. The developments is traced from 1976 till present and the salient achievements are the development of PRIYAGNI (PRI-Power Research Institute) wood burning stove, one of the first designs of compact fluorescent lantern, biomass gasifier and Stirling Engine. On the consultancy side the salient achievement is the energy audit of thermal and hydro power stations across the country. The Division has contributed in its capacity to the making of the Energy Conservation Act 2001, Electricity Act 2003, National Electricity Policy 2005 and all other major energy related legislation.

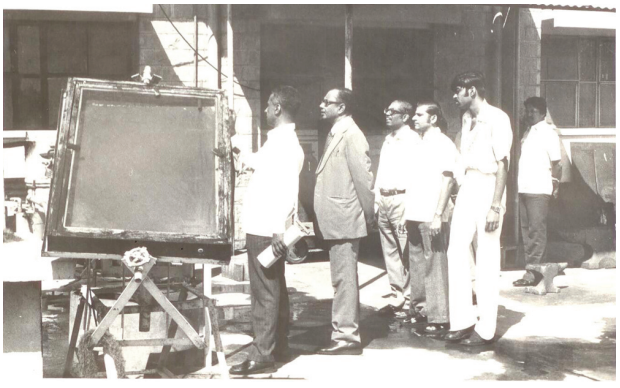
1.0 INITIAL DEVELOPMENTS-RURAL ENERGY LABORATORY (1979–1985)

The 1970s witnessed the Indo-Pak War and the 'Oil crisis' originating from the OPEC members resulted in unprecedented pressure on the availability of both fossil fuels as well as the traditional biomass fuels which triggered the need for developing energy efficient devices and energy conservation technologies. CPRI, among other institutions, responded to this problem of fuel scarcity as a green field entrant through a program of product development leading to energy conservation and utilization of renewable energy. The focus has been on *rural technology and stand-alone remote area applications*.

Product development embrynoated in two areas:

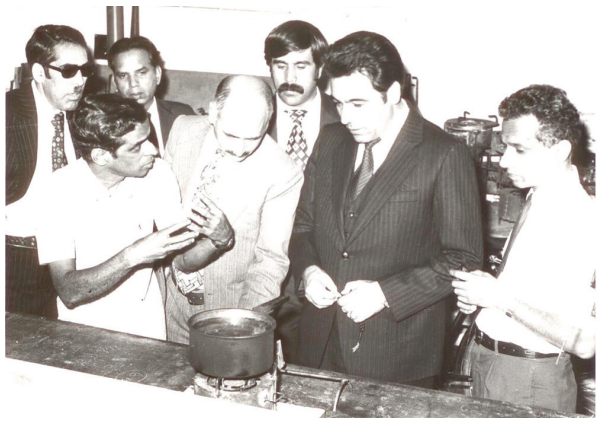
- Wind mill development

CPRI DESIGNED WOOD BURNING STOVE 1981

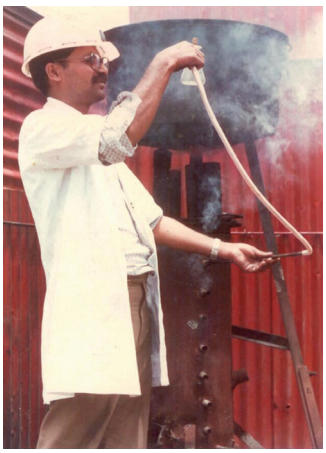


SOLAR WATER HEATER 1981

STEAM OPERATED PISTONLESS PUMP CONSTRUCTION 1981



VISITORS FROM AFGHANISTAN VIEWING WOOD BURNING STOVE 1982



BIOMASS GASIFIER UNDER TEST 1982

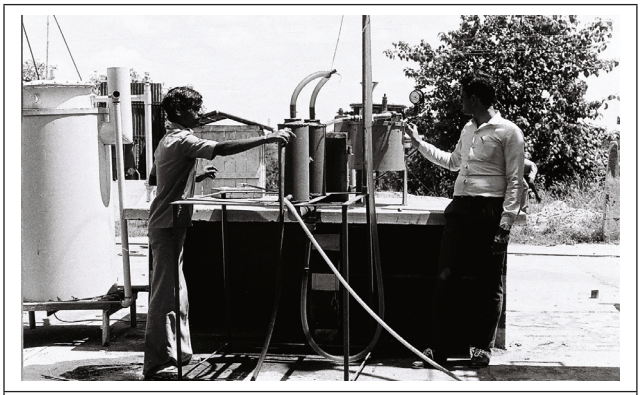
- Water pumping system and wood burning stove

A WP2 water pumping windmill (multi-bladed horizontal rotor with reciprocating pump) was installed at CPRI during 1976 and subsequently models were installed in Tamil Nadu.

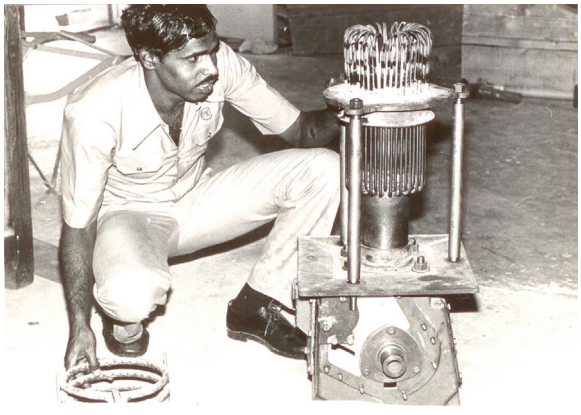
BIOMASS GASIFIER PRODUCER GAS QUALITY CHECKS 1982

VISITORS FROM AFGHANISTAN 1982

A water pumping system (steam operated pistonless pump) without moving parts, based on wood as a fuel was developed to deliver 1.5 m^3/h of water over a head of 10 m consuming 7 kg/h of wood other biomass fuels was developed.

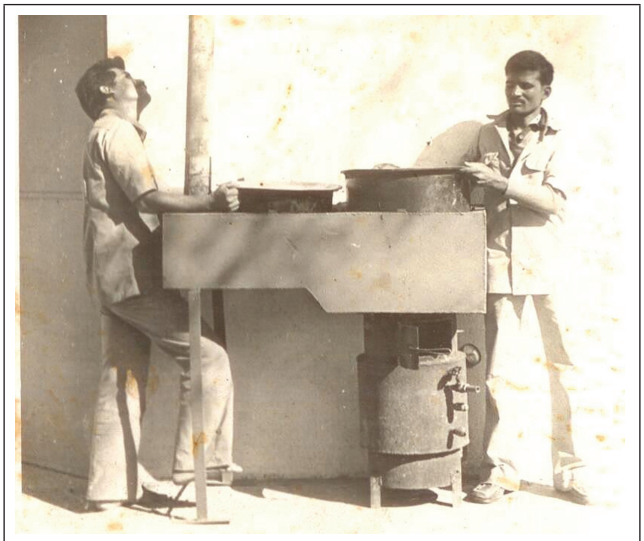


FLUIDYNE PUMP 1982



VIEW OF STIRLING ENGINE UNDER CONSTRUCTION AT CPRI 1983

BIOMASS GASIFIER PERFORMANCE EVALUATION 1983



BIOMASS GASIFIER 1983

In 1979, the Rural Energy Laboratory was established with staff strength of seven. Developmental projects and system studies were taken up by this laboratory which was attached to Instrumentation Division.

In the process of improving the combustion system of this pump, the wood burning stove project was initiated for rural domestic cooking.

Wood burning stove of 0.5 to 10 kg/h of fuel wood was developed to yield efficiencies as high as 35 %. This was the famous PRIYAGNI (PRI-Power Research Institute) which was adopted by the then DNES (later MNES and now MNRE) (presently known as CPRI design wood burning stove) in the cook stove programme and was popularized in every corner of the country and also in other developing countries in South East Asia and Africa.

VIEW OF A WOOD BURNING STOVE DEVELOPED AT CPRI UNDER NATIONAL IMPROVED CHULA MISSION 1983

STEAM OPERATED PISTONLESS PUMP 1984

IMPORTANT VISITORS TO RURAL ENERGY LABORATORY 1984

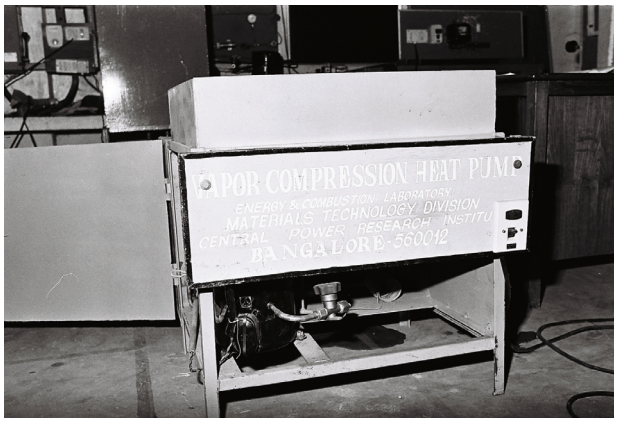
VAPOUR COMPRESSION HEAT PUMP 1985

The main developments during this period were

- *Wood burning stove* (in small medium and large sizes) which efficiently converts energy in wood to heat for domestic cooking. This is a portable metallic stove made of cast iron or mild steel with an aluminum reflective liner inside and optimal combustor height and optimal flame-vessel spacer height.
- *Water pumping windmills* (1 kW). Twisted chamber aerofoil blades of various designs and materials such as plastic wire cane woven over a mild steel frame, fully wooded profile, hollow wooden profile, hollow mild steel profile, etc., were tried out and demonstrated.
- *Steam operated pistonless pump* (as described above) for rural water pumping.
- Updraft biomass gasification as an alternative to combustion route (where the biomass is first converted into producer gas and then combusted at a location away from the conversion zone) was studied and led to the development of *updraft biomass gasifier* (10–50 kW at a biomass to heat conversion efficiency of 90%).

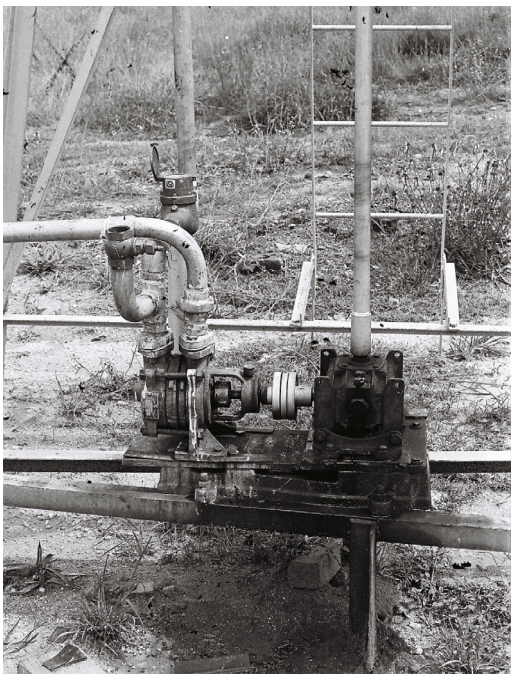
WIND ELECTRIC GENERATOR 1984

WATER PUMPING WINDMILL 1985

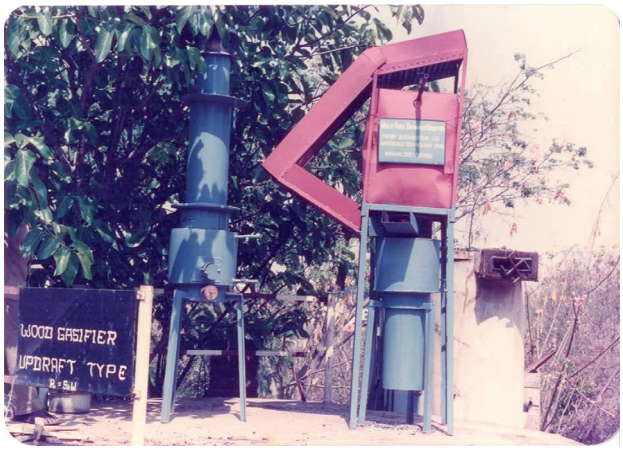


VAPOUR COMPRESSION HEAT PUMP 1985

WATER PUMPING WINDMILL 1985



WIND DRIVEN PUMP 1985



BIOMASS GASIFIER 1986

2.0 R&D IN ENERGY AND COMBUSTION LABORATORY (1985–1991)

In 1984, the staff strength was increased to eight and all energy activities (wind and biomass) were integrated into this division. In 1986, the Rural Energy Laboratory was renamed as Energy and Combustion Laboratory and attached to Materials Technology Division. Besides renewable energy, conventional electric power and fossil fuels were also added to the scope of R&D.

The developments during this period included:

- *Stirling Engine system* for water pumping (3 kW) using an improved combustor. The Stirling engine is an external combustion engine using air at 2 kg_f/cm^2 as the working fluid with heating from a heat source outside. Hence the system is independent of the fuel used. The classical air standard Stirling cycle is composed of two constant volume processes and two constant temperature processes. The four processes are achieved cyclically by passing the air through a hot chamber (where it is

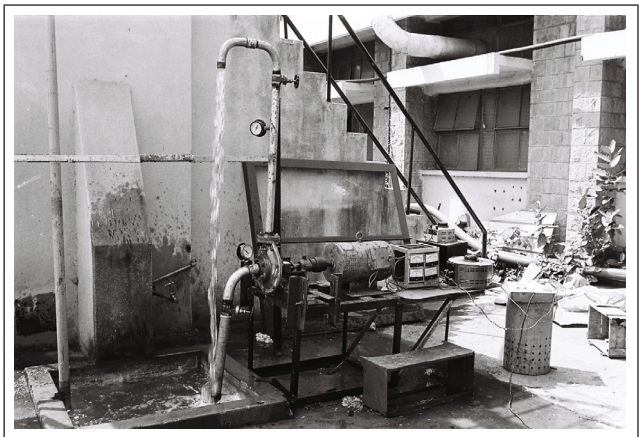
STIRLING ENGINE 1986

heated at constant temperature and volume increase-expansion). It is then passed into a regenerator (heat exchanger which transfers the heat from the hot fluid to the returning cold fluid- constant volume process). The fluid then goes into the cold chamber (which undergoes constant temperature volume decrease-compression). The cold fluid then gets heated through the other side of the regenerator (constant volume process). This cyclic process repeats. The output of the Stirling engine is directly coupled to a centrifugal water pump.

- *Updraft biomass gasifiers* as a substitute for inefficient traditional rural combustors.
- *Gas-water heat exchangers* for hot air generation from biomass gasifier.

WIND GENERATOR 1986

- *Gas-air heat exchangers* for hot water generation from biomass gasifier.
- *Wind electric generators* (2 kW) – 3 bladed airfoil camber design twisted blades (7.85 m rotor ϕ) of polythene cane woven over steel frames. The tower is lattice type (11 m). These are designed for low wind regimes (cut in speed: 3 m/s; rated speed: 7 m/s and cut-out speed: 11 m/s) with high sweep protection through dis-engaging tail vane through an auxiliary vane and manual pitch control. Measured efficiencies are 20–22%.
- *Water pumping windmill* through electric route. The wind power is converted into electric power (DC) and transmitted to energize the DC powered submersible pump sets.
- *Vapor compression heat pump* (3 kW) in which electric power is used as the actuating energy source, ambient air as the heat source, hot water as the output energy product and Freon 22 as the working fluid in a hermetically sealed reciprocating compressor circuit. For every 1 kW of electric power input around 3 kW of thermal power at 55ºC is obtained. The balance of 2 kW is extracted from the ambient air. The system is based on the air standard refrigeration cycle which consists of isentropic compression (in the compressor), constant pressure heat withdrawal (in the condenser which delivers hot water by condensing the refrigerant at a high pressure), isentropic expansion



DC GENERATOR FOR WINDMILL 1988

(expansion valve) and constant pressure heat addition (evaporator where the heat from the ambient air is used to evaporate the refrigerator at a low pressure).

The first CPRI energy audit was taken up at M/s. National Industries, Magadi Road, Bangalore in 1989 based on a project from MOP for conduct of energy audits in three energy intensive industries. The other energy audit was taken up at M/s. Modern Food Industries, Peenya, Bangalore. Another milestone was the first CPRI energy audit in a power station for which Raichur TPS offered Unit No. 1.

3.0 ENERGY RESEARCH CENTRE (1991–2005)

In 1991, Energy and Combustion Laboratory was re-located to Thiruvananthapuram as Energy Research Centre. The staff strength was fourteen. The project right from scratch – land acquisition to commercial operations was co-coordinated by the Energy Group. The Energy Research Centre was located in the picturesque land near College of Engineering, Thiruvananthapuram.

SOLAR AIR HEATER 1996

CANE WOVEN WINDMILL (2 kW) 1992

The broad areas of activities were research, consultancy and testing cum certification in:

- Renewable energy systems –solar thermal , solar photovoltaic, wind and biomass applicable to Rural energy systems,

SOLAR WATER HEATER 1998

DOWNDRAFT BIOMASS GASIFIER WITH ENGINE 1999

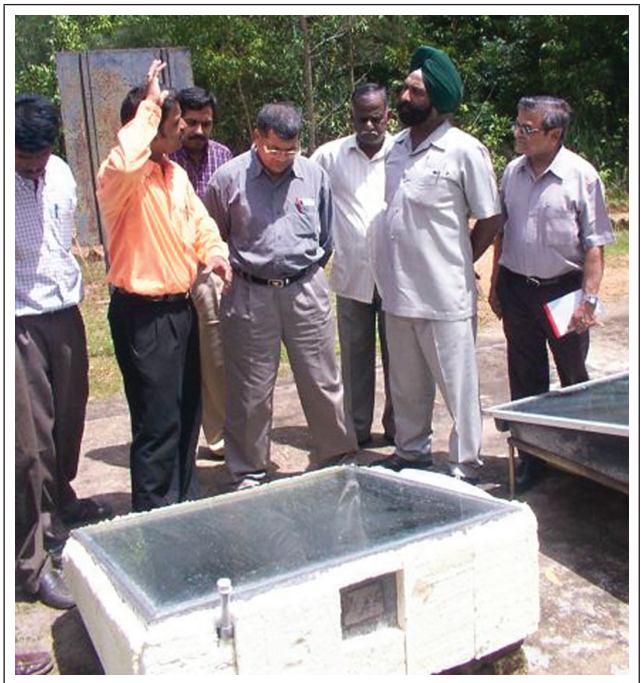
decentralized energy systems, distributed generation and cogeneration.

- Energy efficiency in thermal, hydro power plants, energy intensive industries, commercial buildings, port trusts, etc.
- The concepts of energy labeling and bench marking were gradually taking commercial shape during this period and both laboratory and field evaluation had their background in establishing and measuring benchmarks.

3.1 Technology Development

The Energy Group has developed a large number of energy efficient devices and technologies. These have been field tested and transferred to a large number of industries and entrepreneurs. Some of these products are as follows:

THERMAL MANAGEMENT-2003



SOLAR STILL-2003

- *High efficiency inverters* for photovoltaic applications (5 kW and efficiency of 90%). In renewable energy systems like photo-voltaic systems where the capital cost of the system is very high (typically ₹ 3.0 lakhs/kW and above) the efficiency of the balance of the system is very critical and every attempt is required to operate the balance of plant at the highest efficiency and avoid system losses. The high efficiency inverters are developed for photovoltaic applications.
- *Multi-fuel biomass gasifier* (10–50 kW). The system accepts a variety of biomass fuels.
- *Stirling engine power pack* (5 kW) system. The Stirling engine is coupled to a generator which is connected to a lamp load. The main conversion is through a Stirling engine energized by a biomass gasifier and the mechanical output being connected to an electric DC generator (firing rate 10–50 kg/h; Thermal input: 60 kW_t). The load is controlled through a rectifier cum charger, inverter and PLC controller. The bulk of the energy is supplied through the Stirling

ENERGY RESEARCH CENTER AT TRIVANDRUM 1994

Engine and the balance is through a backup unit comprising of DG set energized by downdraft gasifier (firing rate: 4–6 kg/h).

- *Vapour compression heat pump* (50 kW) based on screw compressor technology, plate fin and tube heat exchangers for evaporators and condensers and thermostatic expansion valves. This provides hot water at 50-55 ºC.
- *Solar lantern* based on unique control circuitry.
- *Wind-diesel-solar photovoltaic integrated energy systems (2 kW)* for remote applications. The main features are low cost, light weight polythene cane woven blades, gear box, low speed self regulating DC generator (2 kW), DG set (3.5 kVA), battery bank and electronic controller (inverter-rectifier cum charger).
- *Street light controllers* based on photosensitive light switching /PLCs.
- *Condensate depression monitor.* This is a microcontroller (8031) based instrument with embedded software for measuring and displaying condensate sub-cooling (an undesirable phenomenon) in a condenser of a thermal power plant. The condensate is supposed to condense at the saturation temperature because it is subsequently heated in the feed heaters. If it is sub-cooled, this additional heat gets loaded onto the feed heaters.
- *Solar PV refrigerator for vaccine storage.* The system consists of photovoltaic modules (70 W_p), refrigerator control unit (RCU), charge controller, positive plate tubular lead acid maintenance free batteries (12 V × 180 Ah × 4 nos.) and refrigerator (1 kVA, 230 V, 50 Hz).
- *Low cost solar water heaters* based on locally available materials.
- *Solar wax melting system* useful for melting around 10 kg of wax at a time in the storage tank of a flat plate water heater. This molten wax is then poured into candle moulds.
- *Solar stills* useful for producing around 5 kg of water per day from brackish water. This is a blackened flat plate condensing still.
- *Thermal energy meter.* This is a micro controller based embedded software instrument for measuring and continuously displaying the efficiency of a solar water heating system which consists of a large storage tank, a large number of panels

STEEM OPERATED PUMP 2005

(10 m^2 and above) and a multi-user, round the clock extraction without communication between individual users (as in hostels). In such collectors where one or more modules are out of order, the drop in efficiency does not get noticed because each user attributes it to the others. This instrument measures thermal energy in the tank through a series of thermocouples, the solar input through a calibrated photovoltaic cell and computes the collector efficiency, if one or more cells are out of order, the monitor displays the same though it does not identify the exact cell.

- *Laser based coal flow monitoring system* for measuring pulverized coal in pipes leading from the mill to the coal burners.

3.2 Energy Audit

The well known tool for improvement in energy efficiency is the energy audit which is a process of measuring energy efficiency of processes, equipment, sub-systems and systems and comparing these with standard benchmarks and best practices for evolving efficiency improvements. Technical energy audits (with aims ranging from identifying ways of conserving energy to evolution of a new blue print for the energy system) provide insight into the modes of better energy utilization. The *energy audit* are undertaken both on thermal and electrical systems in a wide range of industries and power stations. The experience is fully support by measurement, experimental and computational capabilities. The detailed findings of the energy audit are brought out in the form of a consolidated report, which gives analysis, conclusions and recommendations for energy efficiency measures.

CPRI had conducted instrumented and diagnostic energy audits in over 120 thermal power plants as follows:

[1] Sponsored by Ministry of Power. Govt. of India, New Delhi – 20 units.

[2] Performance enhancement in thermal power plants through tuning of equipment during capital/annual overhaul for 7 thermal power plants sponsored by Ministry of Power, Govt. of India, New Delhi. In this scheme, we had conducted energy audit/performance test before overhaul, suggested simple energy conservation measures, participated in overhaul for implementing the energy conservation measures and conducted performance test after the overhaul to quantify the energy saving. Thereby we have demonstrated energy saving to the tune of 3.7-8.1 t/h of coal, 300–800 kl/year of fuel oil and 270–1450 MWh/month of electric power.

[4] For National Thermal Power Corporation (NTPC) and Govt. Owned GENCOs and DISCOMs owned thermal power plants for improvement in the performance of boilers, turbine, generators, auxiliary power systems, coal handling plants, ash handling plant, water circulating system, compressed air systems, etc.

[5] As a basis for renovation, modernisation and uprating of TPS in nearly 10 plants where the focus is on regaining of lost capacity, restoring of efficiency to design values or better and meeting new environmental norms.

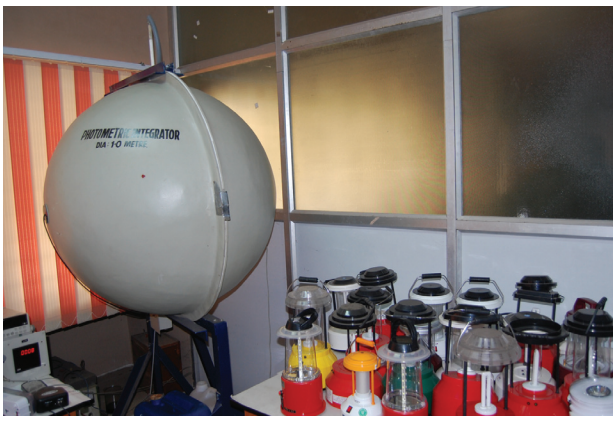
[6] In its capacity as independent, impartial third party agency CPRI is involved in matters of heat rate and power plant KPI for Regulatory Commissions.

4.0 ENERGY EFFICIENCY AND RENEWABLE ENERGY (2005–PRESENT)

In 2005, the Energy Conservation and Development Division was re-started in Bangalore re-named in 2011 as Energy Efficiency and Renewable Energy Division.

4.1 Research Activities

Research activities have been aimed at studies on development of technologies based on solar thermal and photo voltaics, new thermodynamic cycles for power plants and air conditioning;



ILLUMINATION LABORATORY-2008

problems related to heat transfer in cooling towers, heat exchangers; instrumentation for identification and improvement of energy efficiency, technologies aimed at increasing the energy efficiency of auxiliaries in coal fired thermal power plants, studies in solid illumination technologies.

4.2 Consultancy Services

The primary field consultancy studies are energy audits in thermal power stations, hydel power stations and energy audits in industries including refineries, buildings, port trusts, etc.,

Thermal power plant related consultancy is provided in the following areas:

- Studies on retrofitting of turbines with new 3-d blades-dispute resolution
- Renovation, modernization and upgradation studies of coal fired thermal power plants
- Fixing of rational heat rate for a thermal power plants

The Energy group has also provides Consultancy for technical evaluation, general engineering, detailed engineering and implementation of energy efficiency measures related to:

- Combined heat and power (CHP) and co-generation
- Tuning of fossil fired furnaces (coal, gas and oil) and thermal insulation
- Power factor improvement, improved distribution systems, transformer management to minimize overall loss profile
- Process integration and super-targeting using heat exchanges; thermal energy recover through feedback such as air pre-heating, regeneration, recuperation, feed heating, etc.
- Performance evaluation and tuning of Thermal Power Stations before, during and after overhaul.
- Field performance evaluation of grid tied and stand alone domestic roof top (1–5 kW) and large solar photovoltaic plant s over 1 MW

4.2.1 Testing and certification

The ERED has facilities for testing and evaluation of energy efficient and renewable energy devices and systems such as solar photovoltaic Lighting system test facility (Approved by Ministry of Non-conventional and Renewable Energy).

4.2.2 Knowledge dissemination and training

ERED has been conducting periodic Workshops and Conferences to bring out new advances in technology and best practices on topics of current interest for professionals. The National Conference on Technology Advances for new power generating units and for performance

FIRST LED BEING TESTED AT ERED-2008

NATIONAL CONF ON LEDS-2010

enhancement of present plants (Nov. 18–19, 2011) was aimed at the power generating sector where capacity addition is going at a brisk pace of 10+%/year. Similarly in the area of LED lighting systems, a National Conference on Recent trends and technological advances in LED lighting systems (13–14 Dec. 2011) was held. Recently, a Two days Tutorial Programme on, '*Case studies of Energy Conservation in Water pumps and Pumping Systems*', organized by ERED during 27–28th February 2012 at S. J. Auditorium, CPRI, Bangalore.

On the training side Certification course in Safety, thermal power plant efficiency improvements, electrical networks, etc., have been conducted. The Division has provided facilities for over 120 B.Tech, 38 M.Tech and one Ph.D student for carrying out their project work.

5.0 PLANNING FOR THE FUTURE

The good installed capacity (200 GW-31-03-2012), focused growth of solar PV (1 GW) and wind based generation (15 GW) has ensured that sustainable growth (8+%) is being maintained through fossil-renewable composite capacity addition.

The two upcoming areas in the near future are capacity addition of coal fired thermal power plants and renewable energy. In the area of coal fired thermal plants ultra super critical (USC) power plant cycle and integrated gasification combined cycle (IGCC) conversion route are the immediate areas of interest.

In the renewable energy are solar photovoltaic based grid connected roof top (3–10 kW) and centralized power plants (1–20 MW) are increasingly coming into use. Development of high efficiency thin film and organic sells and concentrated PV and new areas. Solar flat plate collector technology has almost stabilized.

TRAINING PROGRAM ON PUMPS ERED 5-6 MARCH 2012

PRESENT LOCATION OF ENERGY EFFICIENCY & RENEWABLE ENERGY DIVISION

However, the technology of concentrating collectors is still under the developmental cycle.

On the energy efficiency of individual equipment the current areas of interest are:

1. High efficiency batteries with MW storage capacity of sodium ion type.
2. High efficiency solid state illumination systems.
3. 3-d CFD design of blades and passages of fluid elements such as turbines, pumps, etc.
4. Steam path audits for estimation of degradation of operational performance of turbines with age.
5. Evaluation of optical characteristics of glasses and glazes used in solar energy utilization and building.
6. Performance optimization gas power plants and bagasse based cogeneration plants.
7. Solar energy and wind data for guaranteeing the performance of solar and wind equipment.
8. Instrumentation and control strategies for renewable energy systems.

On the thermal front heat storage and recovery systems and technologies for ventilation, heating and cooling with heat recuperation; and biomass to fuel conversion processes are coming into prominence.

The upcoming areas are solid state multi pulse power converters AC/AC (cyclo converters), AC/DC (converters), DC/AC (inverters) and DC/DC) with a variety of technologies like UPS, inverters, rectifiers, etc. configured by active front end PMW converters, multi pulse converters, full wave and half wave uncontrolled, half and fully controlled converters, etc. These technologies are powered by a variety of devices

like IGBTs, GTOs, MOS controlled thyristors (MCTs), carrier charge storage trench gate bipolar transistors (CSTBTs), diodes, thyristors, etc.

Variable frequency drives with programmable sequences of a range of torque-speed combinations, acceleration and declaration with external feedbacks are rapidly replacing the mechanical speed change technologies like gear boxes, belt drives, chain drives, etc.

Active and passive harmonic filters for power harmonic control are also gaining importance.

Consultancy services are focused on energy audits, energy efficiency performance evaluation of hydro and thermal power plants and process industries. Renovation, modernization and upgradation studies of power plants and industrial power networks is also another area. On the renewable energy front consultancy services are directed towards field evaluation of large grid connected photovoltaic plants and of multi-source distributed generation systems in rural micro grid configurations.

Test facilities envisaged are for solar lantern test facility to be upgraded with more number of tests and more number of samples at a time. Solar LED lighting systems including home lighting, street lighting and commercial office lighting systems are upcoming. Testing and certification of Grid tied inverters and AC coupled inverters, uninterrupted power supply, voltage stabilizers, etc. for solar photovoltaic and grid connected applications is the other area. The solar thermal collector evaluation involves concentrating collectors and solar thermal collector test rig suitable for testing five collectors at a time.

The instrumentation for the test rigs will be based on the DCS concept of primary sensors-electrical conversion-digital conversion-data acquisition through computers and computer console. This will enable modularity and ease inter-communication between the various instruments.

Dissemination of state of the art knowledge through Workshops and Conferences has been seamlessly integrated with the consultancy activities.

6.0 CONCLUDING REMARKS

CPRI has over a quarter century of experience in energy technology development. The developments is traced from 1976 till present and the salient achievements are the development of PRIYAGNI wood burning stove, one of the first designs of compact fluorescent lantern, biomass gasifier and Stirling Engine. On the consultancy side the salient achievement is the energy audit of thermal and hydro power stations across the country. It is fully equipped to provide energy services and meet upcoming challenges of indigenous capability building in technology development, system studies and implementation in the areas of renewable and fossil fuel energy and in the Indian electric power sector.

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The Division owes itself to the contributions of the pioneers Shri V.K. Narasimhan, S. Jayaraman (late), Dr. S. Parameshwaran, Dr. M. Ramamoorty, Dr. P.R. Krishnamoorthy (late), R.K. Hegde, S. Seetharamu, B.H. Narayana, V.N. Nandakumar, V.K. Ramu, R.S. Kamalakar, S.L.V. Nityananda, B.S. Ramesh (late), C. Dattatri, Dr. Subhakar, Dr. J. Ramamohan Rao and R. Sudhir Kumar.

Among the technicians the contributions of M. Thomas, M. Sagairaj, Andanappa (late) are recognized.

Present DG's keen encouragement is acknowledged.

BIBLIOGRAPHY

[1] Siddhartha Bhatt M. "The efficiencies of firewood devices (Open fires, Chulahs and Heaters", *Proc. Ind. Acad. Sci. (Engg. Sci.),* Vol. 5, No. 4, pp. 327–342, December 1982.

[2] Siddhartha Bhatt M. "The design of rural energy systems", *Proc. Ind. Acad. Sci. (Engg. Sci.),* Vol. 7, No. 3, pp. 237–258, Nov. 1984.

[3] Siddhartha Bhatt M. "Industrial and domestic energy consumption in Nellore Villages", *Proc. Ind. Acad. Sci. (Eng. Sci.),* Vol. 7, No. 4, pp. 315–328, Dec. 1984.

[4] Siddhartha Bhatt M. "Progress in wood stove technology", *Journal of Sci. Ind. Res.,* Vol. 43, pp. 366–379, July 1984.

[5] Jayaraman S, Siddhartha Bhatt M and Rao R.M. "Studies on thermal performance of certain wood stoves and design of a high efficiency stove", *International Journal of Energy Research*, Vol. 13, pp. 103–122, Jan. 1989.

[6] Vimal O. P. and Siddhartha Bhatt M. "Wood Energy Systems", K.I. Publishers, New Delhi, pp. 285, 1989.

[7] Siddhartha Bhatt M. "Towards the design of high efficiency woodstoves", *International Journal of Energy Research*, Vol. 14, pp. 629–649, 1990.

[8] Siddhartha Bhatt M. "Thermal rating and design of woodstoves: A new approach", *International Journal of Energy Research*, Vol. 14, pp. 169–180, 1990.

[9] Krishnamoorthy P.R, Seetharamu S. and Siddhartha Bhatt M. "Design optimization of a biomass fueled steam operated pistonless pump", *International Journal of Energy Research,* Vol. 15, pp. 347-356, July 1991.

[10] Krishnamoorthy P.R, Seetharamu S. and Siddhartha Bhatt M. "Development of a novel updraft multi-fuel biomass gasifier, *International Journal of Energy Research*, Vol.15, pp. 377–390, July 1991.

[11] Krishnamoorthy P.R, Seetharamu S. and Siddhartha Bhatt M. "Optimal heat extraction from an updraft biomass gasifier", *Energy Conversion and Management*, Vol. 33, No. 12, pp. 1031–1049, 1992.

[12] Siddhartha Bhatt M., Krishna Murthy M. V. and Seetharamu S. "An absorption-compression heat pump with the new working pair R22-NMP", *Proc. Recent Trends in heat pump design, analysis and application, Advanced Energy Systems Division, ASME*, New York, pp. 27–42, 1992.

[13] Siddhartha Bhatt M, Srinivasan K, Krishna Murthy M. V. and Seetharamu S. "Thermodynamic modelling of absorption-compression heating cycles with some new working pairs", *JSME International Journal*, Series II, Vol. 35, No. 4, pp. 662–672, 1992.

[14] Siddhartha Bhatt M, Srinivasan K, Krishna Murthy M. V. and Seetharamu S. "Thermodynamic modelling of absorption resorption heating cycles with some new working pairs", *Journal of Heat Recovery Systems and CHP*, Vol. 12, No. 3, pp. 225–233, 1992.

[15] Siddhartha Bhatt M. and Seetharamu S. "Energy conservation in fossil-fuel-fired systems: Three case studies", *International Journal of Energy Research*, Vol. 17, pp. 537–559, 1993.

[16] Thyagarajan K, Siddhartha Bhatt M. and Sudir Kumar R. "Economics of solar photovoltaic systems with high efficiency conversion chains", *Renewable Energy,* Vol. 5, Part III, pp. 1614–1616, 1994.

[17] Siddhartha Bhatt M, Thyagarajan K and Kamalakar R.S. "Integrated solar, wind and diesel units for 10 kW electric power generation"*, Renewable Energy*, Vol. 5, Part III, pp. 1617–1619, 1994.

[18] Thyagarajan K, Mandi R.P, Sudir Kumar R. and Siddhartha Bhatt M. "Efficient control for hybrid energy systems", *Applied Energy*, Vol. 52, No. 2–3, pp. 255–263, Aug. 1995.

[19] Siddhartha Bhatt M. and Seetharamu S. "Energy conservation in 210 MW coal fired thermal power plants, International Journal of Energy Research, Vol. 19, No. 6, pp. 515–534, Aug. 1995.

[20] Siddhartha Bhatt M, Mandi R. P. and Nandakumar V.N. "Integration of energy systems in the small capacity range", *Energy Sources*, Vol. 20, No. 4–5, pp. 407–426, May-June 1998.

[21] Siddhartha Bhatt M. "Revamping of industrial heaters for improving energy efficiency at peak thermal power output point", *Reviews in Process Chemistry and Engineering,* Vol. 2, No. 2, pp. 85–110, 1999.

[22] Siddhartha Bhatt M and Seetharamu S. "Control of slagging in lignite fired power boilers, *Reviews in Process Chemistry and Engineering*, Vol. 2, No.3, pp. 195–212, 1999.

[23] Siddhartha Bhatt M. "Control of performance deterioration in solar water heating systems", *International Journal of Renewable Energy Engineering*, Vol. 2, No. 3, pp.214–220, 2000.

[24] Siddhartha Bhatt M. and Jothibasu S. "Performance enhancement in coal fired thermal power plants. Part I: Boilers", *International Journal of Energy Research*, Vol. 23, pp. 465–487, 1999.

[25] Siddhartha Bhatt M and Rajkumar N. "Performance enhancement in coal fired thermal power plants. Part II: Turbines, *International Journal of Energy Research*, Vol. 23, pp. 489–515, 1999.

[26] Siddhartha Bhatt M. and Mandi R.P. "Performance enhancement in coal fired thermal power plants. Part III: Auxiliary power, *International Journal of Energy Research,* Vol. 23, pp. 779–804, 1999.

[27] Siddhartha Bhatt M, Mandi R.P, Jothibasu S and Rajkumar N. "Performance enhancement in coal fired thermal power plants. Part IV: Overall system", *International Journal of Energy Research*, Vol. 23, pp. 1239–1266, 1999.

[28] Siddhartha Bhatt M. "Energy audit case studies I-steam systems", *Applied Thermal Engineering,* Vol. 20, pp. 285–296, 2000.

[29] Siddhartha Bhatt M. "Energy audit case studies II-air conditioning (cooling) systems", *Applied Thermal Engineering*, Vol. 20, pp. 297–307, 2000.

[30] Siddhartha Bhatt M. and Mandi R.P. "Modernization and energy conservation in a ceramic kiln", *Reviews in Process Chemistry and Engineering*, Vol. 3, No. 1, pp. 01–44, 2000.

[31] Siddhartha Bhatt M. and Sudir Kumar R. "Energy conservation in a caustic soda plant", *Reviews in Process Chemistry and Engineering*, Vol. 3, No.1, pp.45–65, 2000.

[32] Siddhartha Bhatt M and Sudir Kumar R. "Performance analysis of solar photovoltaic plants-Experimental results", *International Journal of Renewable Energy Engineering*, Vol. 2, No. 2, pp. 184–192, 2000.

[33] Siddhartha Bhatt M. "Control of performance deterioration in solar water heating systems", *International Journal of Renewable Energy Engineering*, Vol. 2, No. 3, pp. 214–220, 2000.

[34] Siddhartha Bhatt M. "Energy efficiency and greenhouse emission burden from coal fired electric power plants-A case study of the Indian power sector", *Energy Sources,* Vol. 22, pp. 611–623, 2000.

[35] Siddhartha Bhatt M and Rajkumar N. "Mapping of Combined Heat and Power Systems in sugar industry", *Applied Thermal Engineering,* Vol. 21, 1707–1719, 2001.

[36] Siddhartha Bhatt M. "Mapping of General Combined Heat and Power Systems", *Energy Conversion and Management*, Vol. 42, 115–124, 2001.

[37] Siddhartha Bhatt M and Vinita Chellapan. "Control of specific energy consumption

and energy efficiency in selected industries for CO_2 mitigation", in *Energy Research at the Cutting Edge (ed. John R. Blackwood)*, Nova. Science Publishers Inc., New York, pp. 95–122, 2002.

[38] . Siddhartha Bhatt M. "Effect of ash on the performance of coal fired thermal power stations Part I (Primary energy effects)", *Energy Sources*, Vol. 28, pp. 25–41, 2006.

[39] Siddhartha Bhatt M. "Effect of ash on the performance of coal fired thermal power stations Part II (Capacity and secondary energy effects", *Energy Sources*, Vol. 28, pp. 43–58, 2006.

[40] Siddhartha Bhatt M. "Effect of water side deposits on the energy performance of coal fired thermal power plants", *Energy Conversion and Management*, Vol. 47, No. 9-10, pp. 1247–1263, June 2006.

[41] Siddhartha Bhatt M. "Effect of air ingress on the energy performance of coal fired thermal power plants", *Energy Conversion and Management*, Vol. 48, No. 7, pp. 2150–2160, June 2007.

[42] U C Aurnachala, Siddhartha Bhatt M and Sreepathy L K. "Scaling effect of direct solar hot water systems on energy efficiency", *Trans. ASME Journal of Solar Energy Engg.*, Vol. 132, pp. 041012-1 to 041012-10, November 2010.